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Development of the Low Swirl Injector for Fuel-Flexible Gas Turbines

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Industrial gas turbines are primarily fueled with natural gas. However, changes in fuel cost and availability, and a desire to control carbon dioxide emissions, are creating pressure to utilize other fuels. There is an increased interest in the use of fuels from coal gasification, such as syngas and hydrogen, and renewable fuels, such as biogas and biodiesel. Current turbine fuel injectors have had years of development to optimize their performance with natural gas. The new fuels appearing on the horizon can have combustion properties that differ substantially from natural gas. Factors such as turbulent flame speed, heat content, autoignition characteristics, and range of flammability must be considered when evaluating injector performance. The low swirl injector utilizes a unique flame stabilization mechanism and is under development for gas turbine applications. Its design and mode of operation allow it to operate effectively over a wide range of conditions. Studies conducted at LBNL indicate that the LSI can operate on fuels with a wide range of flame speeds, including hydrogen. It can also utilize low heat content fuels, such as biogas and syngas. We will discuss the low swirl injector operating parameters, and how the LSC performs with various alternative fuels.

1. Introduction

In response to stricter emissions regulations, industrial gas turbine manufacturers are implementing lean premixed (Dry Low NO_x, or DLN) combustor designs on their power turbines. NO_x emissions limits are being reduced in regions with on-going air quality problems, and the DLN combustors must be operated at very lean conditions to satisfy these lower emissions limits. Many DLN systems exhibit operational difficulties near the lean limit, including noise, flame instability, and flame blowout. Manufacturers are exploring a range of options to achieve the ultra-low emissions requirements, including active and passive combustor controls, catalytic combustors, and post-combustion NO_x removal with systems such as SCR. However, all of these methods add cost and complexity to the turbines.

As natural gas cost and availability becomes more of a concern, there is increasing interest in operating gas turbines on alternative fuels. Fuels under consideration include renewable fuels with lower heat content than natural gas, as well as high-hydrogen fuels such as syngas. These fuels can have significantly different combustion properties than natural gas, such as flame speed and heat output. DLN combustor designs may require modification to operate properly on alternative fuels.

The low swirl injector (LSI) was conceived at LBNL [1-3] and has been under development as a DLN technology for natural gas-powered turbines [4]. The LSI has a unique flame stabilization mechanism that provides good flame stability and very low emissions at lean operating conditions. The low swirl design has been licensed for process heating applications by Maxon Corporation, and is under development for turbine applications. Engine tests have been conducted of the LSI on both mid-sized power turbines and microturbines fueled with natural gas.

With increasing interest in alternative fuels, there is a need to adapt low emission combustors such as the LSI to these fuels while maintaining low emissions and good flame stability. In this study, we report the results of studies to explore the performance of the LSI when operating with high hydrogen fuels and low heat content fuels such as biogas.

2. Background

The low swirl injector has evolved from a burner concept that was originally developed for fundamental laboratory studies of turbulent flames [1]. Measurements and analysis of flames generated by low swirl combustors have provided insight on the basic operating principle. Low swirl combustion is an aerodynamic flame stabilization mechanism that utilizes a diverging flow to allow a premixed turbulent flame to freely propagate. The combustor design is simple, robust, and adaptable to many configurations and operating environments. Low swirl flames display good stability at the very lean conditions necessary to achieve ultra-low emissions.

Recent work at LBNL and Solar Turbines has led to the development of a low swirl injector adapted to mid-sized power turbines [5]. Photos in Figure 1 show the LSI in operation and the interior components of the LSI. A cross-section of the LSI is shown schematically on the right side of Figure 1. The flow through the LSI is split between a non-swirling central core flow and a

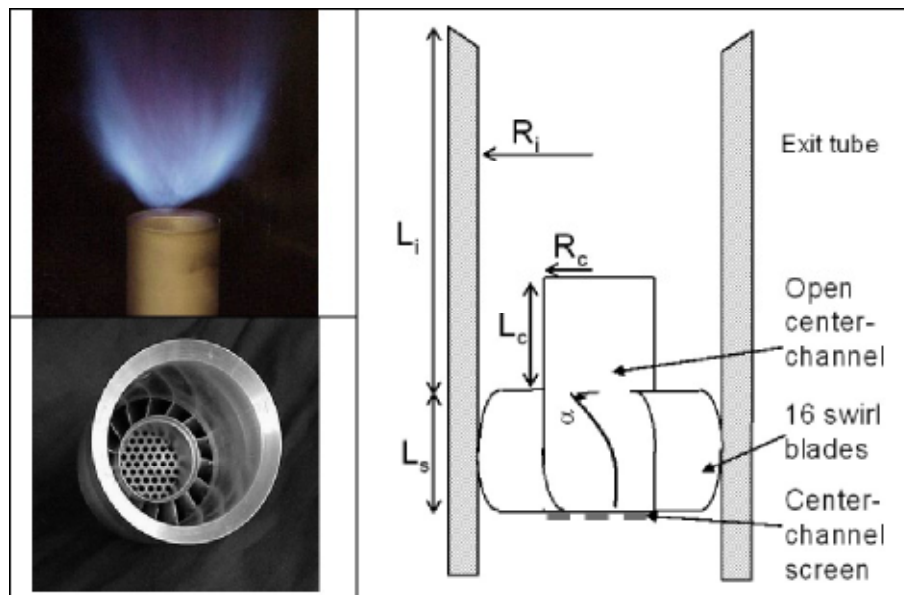


Figure 1. Photos of the low swirl combustor and a cross-section view of the LSC components.

swirling outer annular flow. The two flows interact to generate a diverging flowfield at the throat of the injector. The equation for the swirl number, S , for the LSI is shown in Equation 1, and can

be calculated from the swirler geometry and the mass ratio of the center flow (m_c) and the outer swirling flow (m_s), $m = \frac{m_c}{m_s}$. Here α is the exit angle of the vanes that induce swirl on the annular flow, and $R = R_c/R_i$, the ratio of the radii of the center channel and injector. The exit vane angle on the swirler is typically about 40° and R is usually about 0.6. A screen is generally used to adjust the center flow relative to the swirling annular flow to achieve the desired mass flow split and swirl number. Swirl numbers in the range of 0.45 - 0.55 have been found to provide suitable flame lift-off heights for our applications. The exit tube length, L_i , is selected to be in the range of 1.0 to 1.5 times the swirler diameter. This provides a sufficient length for the center and annular flows to interact.

$$S = \frac{2}{3} \tan \alpha \frac{1 - R^3}{1 - R^2 + m^2 \left(\frac{1}{R^2} - 1 \right)^2 R^2} \quad (1)$$

The LSI geometry is generally adjusted to provide a flowfield that avoids significant recirculation, particularly in the nearfield. A strong recirculation zone can contribute to NO_x formation by sustaining the exhaust gas at temperatures that can lead to the formation of thermal NO_x.

Several fuel blends were investigated in this study. The Wobbe Index is the most commonly used parameter to categorize fuels according to their specific heat content. It is defined as:

$$\text{Wobbe Index} = \text{fuel heating value} / (\text{square root of fuel specific gravity}) \quad (2)$$

It is commonly reported in Btu/standard cubic foot, megajoules/standard cubic meter, or kilocalories/standard cubic meter (1000 BTU/scf = 37.3 MJ/m³). Natural gas typically has a Wobbe Index slightly above 1000 Btu/scf. Landfill gas and biogas have Wobbe values below 500; for liquified petroleum gas (LPG) it is about 2000.

One shortcoming of the Wobbe Index is that it does not take into account any combustion properties of the fuel other than heating value. For example, turbulent flame speed is a very important consideration in turbine combustion, particularly for hydrogen-containing fuels. Since hydrogen has a significantly higher flame speed than natural gas, there is justifiable concern about the occurrence of flashback when hydrogen-containing fuels are used in turbine injectors optimized for operation with natural gas.

3. Experimental

A 2.5 inch (6.3 cm) diameter LSI was used for all of the results reported here. For laboratory studies, the LSI was mounted vertically on a cylindrical settling chamber fed by a venturi mixer. The main air flow was supplied by a blower and controlled by a computer-operated damper. The flow rate was monitored with an in-line turbine flowmeter. Fuel and seeder air flows were regulated with mass flow controllers. This facility does not have the capability to preheat the air, so all measurements were made at ambient conditions. This system was used for studies of flow behavior, flame stability, and emissions.

For Particle Imaging Velocimetry (PIV) studies, an auxiliary air flow was supplied to a cyclone seeder containing 0.5 μm alumina particles, and the seeded air was fed into the main flow downstream of the mixer. To observe the flow behavior, the flowfield downstream of the LSI

throat was interrogated by PIV using a New Wave Solo PIV laser with double 120 mJ pulses at 532 nm. A Kodak/Red Lake ES 4.0 digital camera with 2048x2048 pixel resolution captured images with a field of view of approximately 13 cm x 13 cm. The images recorded the nearfield as well as the farfield of the LSI flames with 0.065 mm/pixel resolution. Data acquisition and analysis were performed with software from Wernet [6]. 224 image pairs were collected at each operating condition. The processed data provided approximately 2 mm spatial resolution.

Emissions measurements in the laboratory were obtained using a Horiba PG 250 emissions analyzer. The LSI flame was enclosed with a 20 cm diameter quartz tube to prevent dilution of the exhaust gas, and the sampling probe was placed a few cm above the tube. NO_x and CO concentrations were corrected to 15% oxygen. The analyzer was calibrated periodically using calibration gases with concentrations similar to those observed in the exhaust gases.

A series of fuel blends were used in this study to provide a range of Wobbe Index values and flame speeds so the impact of these properties on the LSI performance could be explored. The fuel blends are summarized in Table 1.

Table 1. Fuels used in this study

Fuel	T _{ad} , K	S _L , cm/s	Wobbe Index*
	@ $\phi = 1$	@ $\phi = 1$	Btu/scf
0.50 CH ₄ /0.50 CO ₂	2013	20	500 for laboratory
0.5-1 CH ₄ , 0.5-0 CO ₂	2013-2210	20-39	500 - 1360 for high pressure
CH ₄	2230	39	1360
0.92 CH ₄ /0.08 H ₂	2230	40	1355 for atmospheric rig
0.60 CH ₄ /0.40 H ₂	2258	57	1230 for laboratory
H ₂	2318	250	1240

* for higher heating value

Additional measurements were performed at the test facilities at Solar Turbines on two test rigs. The first rig is an atmospheric pressure test facility that can provide preheat and flow rates equivalent to turbine operating conditions. The flame is enclosed within a quartz tube and the exhaust is sampled at the exit of the tube. Emissions performance and flame stability were investigated on this test rig. A single injector high pressure rig at Solar allowed the LSI to be studied at pressures, temperatures, and flow rates equal to turbine operating conditions. Testing the LSI at higher preheat and pressure was limited to measurement of emissions and observing flame properties such as lean blowoff behavior.

4. Results and Discussion

The alternative fuels under study can be split into two categories based on combustion properties: low heat content fuels, and fuels with significant hydrogen content. Low heat content fuels typically contain methane diluted with one or more inert species. The diluents act to reduce the flame speed and lower the specific heat content of the fuel. Turbine combustors operating on low heat content fuels will require a higher fuel flow compared to natural gas to achieve their rated heat output. Flame instability and lean blowout are common problems with low heat

content fuels since the diluents reduce the flame speed and the range of flammability. Also, there can be issues with excess emissions of carbon monoxide and unburned hydrocarbons.

Hydrogen-containing fuels, on the other hand, produce higher flame speeds than natural gas and can have a wider range of flammability. This can lead to issues with flashback and difficulty in achieving a satisfactory premixing arrangement. Burning hydrogen-containing fuels at low equivalence ratios can lower the flame speed, but can create problems with inadequate heat output and/or unburned fuel. We discuss here the performance of the LSI at laboratory and turbine conditions when operated on these fuels.

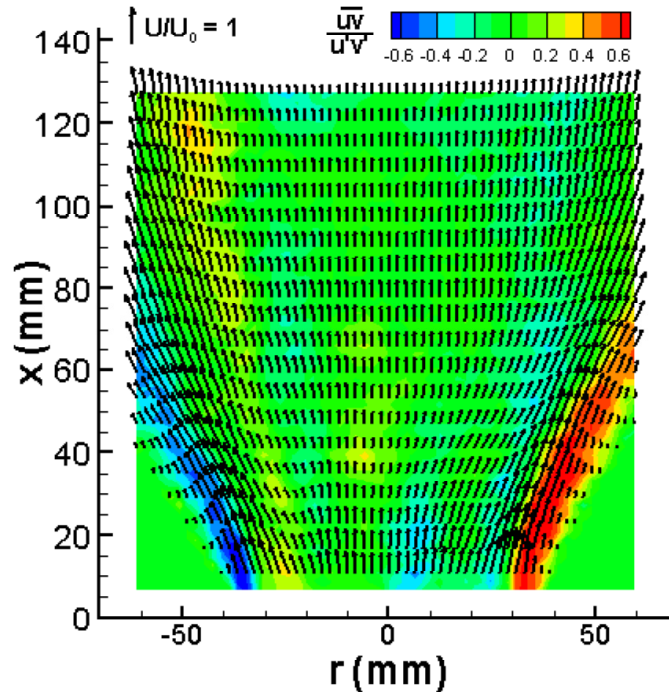


Figure 2. PIV measurement of methane flame at $\phi = 0.7$ and 7 m/s.

We have previously reported [5,7] laboratory studies of the low swirl injector operating on a number of fuel blends, including low heat content fuels and hydrogen-containing fuels. PIV measurements were conducted on reacting and non-reacting flows generated by the LSI to explore the response of the radial and axial stretch rates to the heat release from flames. Figure 2 illustrates the normalized mean velocity vectors and normalized shear stresses $\overline{uv}/u'v'$ for a methane flame. The velocity vectors indicate an absence of a recirculation zone in the flow that is within the field of view.

Analysis of the results of earlier PIV measurements on the low swirl burner and the LSI indicates that the turbulent flame speed correlation is linear over the range of velocities measured, as shown in Figure 3. A virtual origin for the divergent flow at the exit of the injector was defined, which provides a reference point for the divergence [5]. The PIV data indicate that the LSI flows in the nearfield demonstrate similarity, which explains the insensitivity of the flame position to velocity that is observed.

We have now expanded the range of conditions over which the LSI has been studied with low heat content fuels. We previously reported on emissions from the LSI at laboratory conditions, in

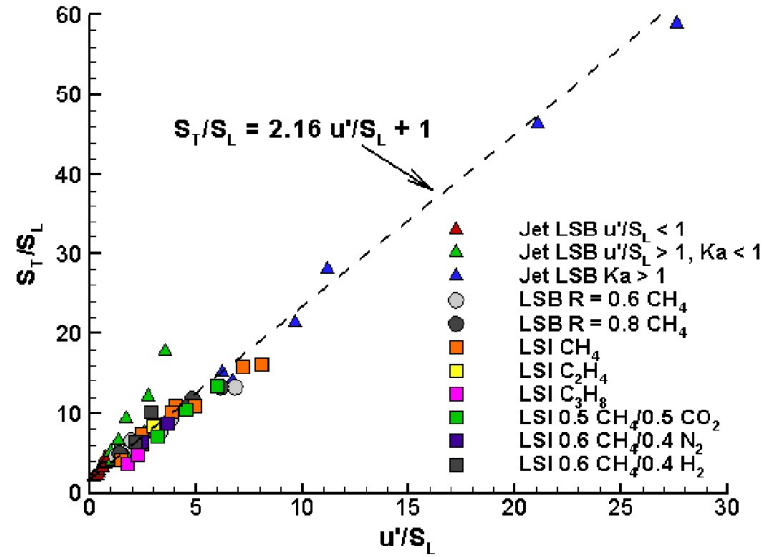


Figure 3. Turbulent flame speed correlation for hydrocarbon flames at laboratory conditions.

which NO_x emissions displayed a log-linear relationship with adiabatic flame temperature [7]. Measurements have been performed in a single injector high pressure test rig with methane-carbon dioxide mixtures with a range of heating values that simulate typical low heat content fuels. The LSI was operated at 60 m/s and 10 atm with 700 K preheat. The data are shown in Figure 4, along with results with a number of different fuels from earlier studies at laboratory conditions. These results indicate that pressure and preheat do not significantly impact NO_x production in LSI flames. Flame temperature is a good predictor of NO_x concentrations over all of the conditions and fuel blends that have been investigated for low heat content fuels.

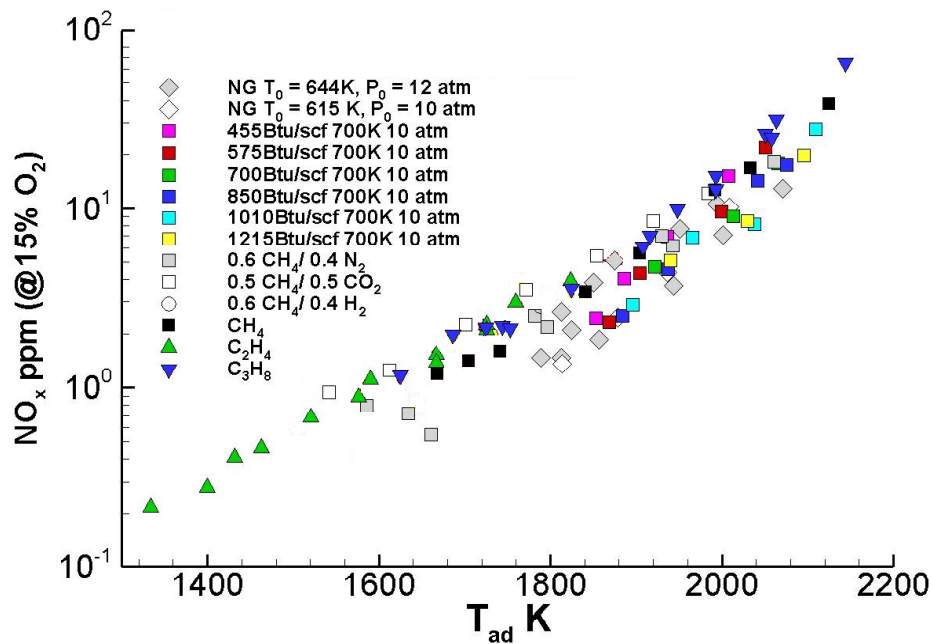


Figure 4. Dependence of NO_x emissions on adiabatic flame temperature.

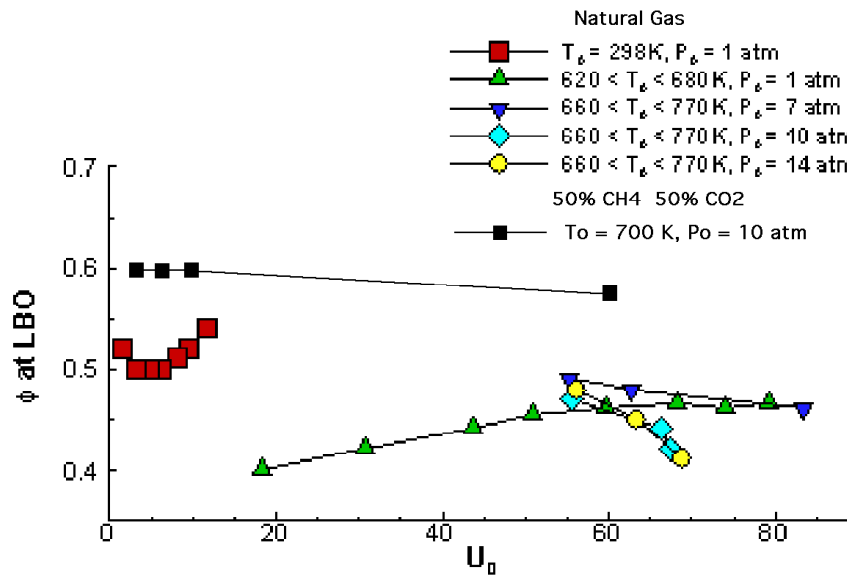


Figure 5. LSI Lean blowoff limits for natural gas and low heat content fuel.

The high pressure rig tests at Solar indicate that the lean blowoff limit for low heat content fuels is not significantly influenced by pressure or velocity, as shown in Figure 5 (black squares). This is consistent with earlier measurements on the LSI fueled with natural gas, also shown in Figure 5. The LSI did not produce excessive noise or other indications of flame instability when operating at lean conditions, indicating that the injector design can operate efficiently on low heat content fuels without modification.

Initial measurements of the LSI performance on hydrogen-containing fuels were made in the laboratory. It is possible to compensate for the high flame speed of hydrogen by operating at lower equivalence ratios than those used for natural gas. The LSI lean blow-off was mapped out as a function of the fraction of hydrogen in the fuel. Addition of even small amounts of hydrogen to methane significantly improves resistance to lean blow-off. We observed that the LSI flame would move upstream and eventually anchor on the rim of the injector as the equivalence ratio was increased above the normal operating range. This behavior allowed mapping of flame stability without generating conditions where the flame would flashback into the injector premix duct. Increasing the operating bulk velocity inhibited flame attachment to the rim.

Studies are underway to explore LSI operation on hydrogen blends at turbine conditions. Due to hydrogen's high flame speed and wide range of flammability, there is concern about the occurrence of unplanned flashback when testing at turbine operating conditions.

As a first step in studying the performance of the LSI on hydrogen-containing fuels at turbine conditions, we have tested the operation of the LSI on methane-hydrogen blends in the atmospheric rig at 730 K preheat and 60 m/s. Even though less than 10% hydrogen (by volume) was added to the fuel, flame stability at lean conditions was significantly improved. As shown in Figure 6, small amounts (4 and 8%) of hydrogen lower the lean blowoff limit and allow operation with extremely low NO_x emissions. The NO_x dependence on adiabatic flame temperature is very similar to that obtained with other fuels (Figure 4). Also, the lean blowoff

values obtained at the atmospheric rig conditions agree well with those obtained in the laboratory.

Additional studies are underway to determine methane-hydrogen flame behavior at ambient conditions and at turbine conditions, and the results will be presented at an upcoming meeting [9]. LSI studies are being initiated in test rigs designed to tolerate flashback events at high pressures and temperatures to explore the behavior of hydrogen fuels at high equivalence ratios and flame temperatures. These studies will allow us to determine the useful operating range for hydrogen fuels and also how to modify the LSI design to compensate for the higher flame speeds associated with hydrogen fuels and to expand the range of stable operation.

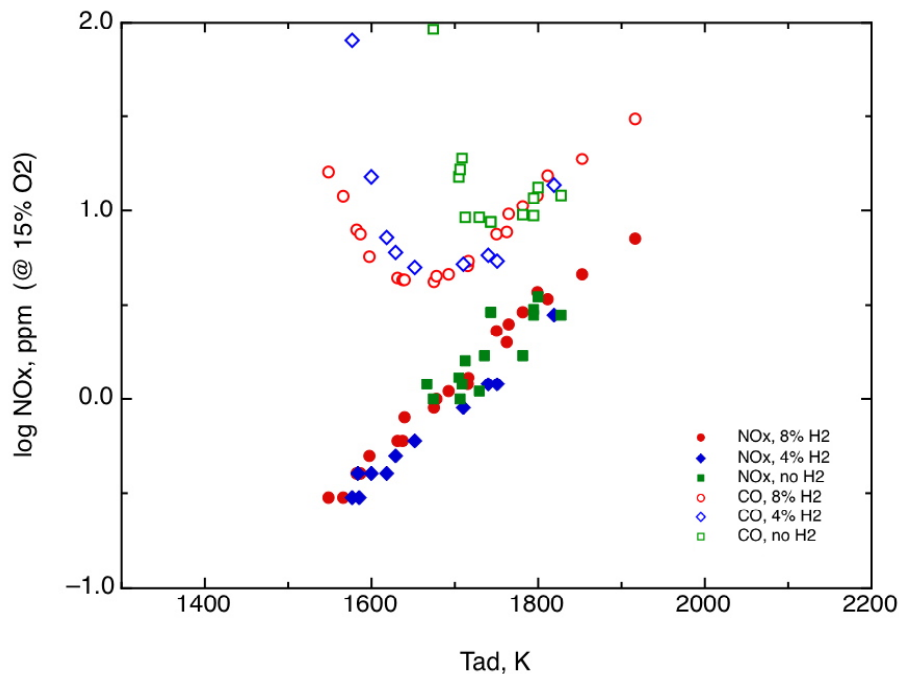


Figure 6. LSI emissions for methane-hydrogen blends as a function of flame temperature.

5. Conclusions

The goal of this research is to develop a LSI-based gas turbine combustor capable of operating on a range of gaseous fuels with little or no modification to the hardware, and to meet the most stringent emissions standards in the country. We have demonstrated that the LSI is adaptable to both low heat content fuels and to hydrogen fuels while achieving ultra-low emissions. It is well-suited for turbines operating on natural gas as well as alternative fuels.

To summarize the results of this and earlier studies on the operation of the low swirl injector, operating pressure and velocity have little effect on lean blowoff. The equivalence ratio at which lean blowoff occurs is reduced by preheating the air-fuel mixture, by adding hydrogen to the fuel blend, or by increasing the swirl number of the LSI. Flame flashback is not significantly affected by pressure. Flashback is inhibited by reducing the LSI swirl number or increasing the operating velocity. Flashback is promoted by preheating the air-fuel mixture or by adding hydrogen to the fuel.

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